A New Type of Extremely Metal Poor Star[1]

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ABSTRACT

We present an abundance analysis for the extremely metal poor star HE1424−0241 based on high dispersion spectra from HIRES at Keck. This star is a giant on the lower red giant branch with [Fe/H] ~ -4.0 dex. Relative to Fe, HE1424−0241 has normal Mg, but it shows a very large deficiency of Si, with ϵ(Si)/ϵ(Fe) $\sim 1/10$ and ϵ(Si)/ϵ(Mg) $\sim 1/25$ that of all previously known extremely metal poor giants or dwarfs. It also has a moderately large deficiency of Ca and a smaller deficit of Ti, combined with enhanced Mn and Co and normal or low C. We suggest that in HE1424−0241 we see the effect of a very small number of contributing supernovae, and that the SNII contributing to the chemical inventory of HE1424−0241 were biased in progenitor mass or in explosion characteristics so as to reproduce its abnormal extremely low Si/Mg ratio. HE1424−0241 shows a deficiency of the explosive α-burning elements Si, Ca and Ti coupled with a ratio [Mg/Fe] normal for EMP stars; Mg is produced via hydrostatic α-burning. The latest models of nucleosynthesis in SNII fail to

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reproduce the abundance ratios seen in HE1424−0241 for any combination of the parameter space of core-collapse explosions they explore.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: abundances — supernovae: general

1. Introduction

Extremely metal poor stars provide important clues to the chemical history of our Galaxy: the role and type of early SN, the mode of star formation in the proto-Milky Way, and the formation of the Galactic halo. The classes and properties of EMP stars are summarized by Beers & Christlieb (2005). The peculiarities discussed there revolve around enhancements of the elements C and N, which are often accompanied by enhancements of the neutron capture elements beyond the Fe peak. Mass transfer within a binary system which occurred while the former primary was an AGB star is an explanation widely suggested for the majority of these peculiarities, including excesses of both CNO and heavy s-process neutron capture elements, see, e.g. Cohen *et al.* (2006).

The number of extremely metal poor (EMP) stars known below [Fe/H] −3.5 dex[1] is very small. We have been trying to increase it through data mining of the Hamburg/ESO Survey (HES) (Wisotzki *et al.* 2000). In this paper we report our discovery of an extremely metal poor star which shows peculiarities in its chemical abundance distribution not seen in any other such star to date that is known to the authors.

2. Stellar Parameters and Analysis

HE1424−0241 (R.A.=14 26 40.3, Dec= −02 54 28, J2000) was observed in May 2004 with HIRES (Vogt *et al.* 1994) at the Keck I telescope. Based on this high resolution spectrum, whose total exposure time was 3600 sec, it was recognized at that time as an interesting EMP star with very low Fe-metallicity. It was observed again with HIRES in April 2006 after the detector upgrade with a total exposure time of 6000 sec. This yielded wider spectral coverage extending far into the UV and a better signal-to-noise ratio than the original data.

[1] The standard nomenclature is adopted; the abundance of element X is given by $\epsilon(X) = N(X)/N(H)$ on a scale where $N(H) = 10^{12}$ H atoms. Then $[X/H] = \log_{10}[N(X)/N(H)] - \log_{10}[N(X)/N(H)]_\odot$, and similarly for [X/Fe].

To determine stellar atmosphere parameters we use the procedures described in Cohen *et al.* (2002) and adopted in all subsequent work by our 0Z project published to date. Our $T_{\rm eff}$ determinations are based on broad band colors $V-I, V-J$ and $V-K$. The IR photometry is taken from 2MASS (Skrutskie *et al.* 2006; Cutri *et al.* 2003). We have obtained new photometry at V and at I for HE1424−0241 ($V = 15.45 \pm 0.03$ mag and $I = 14.54 \pm 0.03$ mag) from ANDICAM images taken for this purpose over the past two years via a service observing queue on the 1.3m telescope at CTIO operated by the SMARTS consortium[2]. We derive surface gravities through combining these $T_{\rm eff}$ with an appropriate 12 Gyr isochrone from the grid of Yi *et al.* (2002). We thus derive $T_{\rm eff}$= 5195 K and log(g)= 2.50 dex. The narrow Balmer lines do not permit the star to be a dwarf below the main sequence turnoff.

The abundance analysis was carried out in a manner similar to those described in Cohen *et al.* (2004). Full details will be given in an upcoming paper which will present the most metal poor stars we have found thus far. If $T_{\rm eff}$ for HE1424−0241 were to be increased by 100 K, the deduced [Fe/H] would increase by 0.15 dex, but the abundance ratios [X/Fe] would be essentially unchanged.

3. Abundances in HE1424−0241

The abundances we derive for HE1424−0241 are given in Table 1. The number of lines used and the σ of the derived log[ϵ(X)] is given for each species for which absorption lines could be detected; upper limits for some key elements are included. These results are compared to the evaluation at [Fe/H] −4.0 dex of linear fits to the abundance ratios determined by our 0Z project of stars from the HES from the 0Z project (many still unpublished) with $T_{\rm eff}$< 6000 K and without substantial carbon enhancement ([C/Fe] < +1.0 dex). In the last column of the table we give same as determined by Cayrel *et al.* (2004) for EMP giants. The dispersion about their regression lines for giants with $-4.2 <$ [Fe/H] < -3.1 dex is small, only 0.11 dex for Mg, 0.20 dex for Si, and 0.11 dex for Ca. The extremely good agreement between the abundance ratios for EMP stars found by these two independent large survey projects, our 0Z project and the First Stars VLT project, and listed in the table is very gratifying, and provides support for our statements about the extreme peculiarities of HE1424−0241.

The anomalies seen in HE1424−0241 are many. The most extreme and most peculiar is the very large deficit of Si, with [Si/Fe] ~ -1.0 dex and [Si/Mg] ~ -1.4 dex, while all other known EMP stars have [Si/Fe] $\sim +0.3$ dex and [Si/Mg] ~ -0.3 dex. [Si/Fe] is low

[2]See http://www.astronomy.ohio-state.edu/ANDICAM and http://www.astro.yale.edu/smarts.

in HE1424−0241 by more than 6σ[3] compared to all other known EMP giants, as is shown in Fig. 1. HE1424−0241 also has a moderately large deficiency of Ca (significant at the 5σ level) and a smaller deficit of Ti. It has enhanced Mn and strongly enhanced Co (significant at the 4σ level), both odd atomic number elements. Copper (another odd atomic number Fe-peak element) may also be enhanced but the single detected line is the rarely observed resonance line at 3274 Å. Carbon is not enhanced and the heavy neutron capture elements Sr and Ba have low abundances relative to Fe, suggesting that mass transfer in a binary system involving an AGB star is not the cause of the peculiar abundance ratios found in HE1424−0241. Each of these anomalies are seen in both the May 2004 and April 2006 HIRES spectra. For example, the equivalent width of the only detected Si I line (at 3905 Å) is 17.7 mÅ from the 2004 spectrum and 13.9 mÅ from the latter one.

No other EMP star shows the low Si/Fe and Ca/Fe ratios seen in HE1424−0241. With one minor exception, no other EMP dwarf or giant that is not C-enhanced is known to show highly statistically significant abundance ratio deviations for any elements between Mg and Ni. (C-enhanced EMP stars sometimes show large enhancements of the light elements, for example CS22949−037, found by McWilliam et al 1995, analyzed again by Depagne et al al 2002.) The exception is the dwarf HE2344−2800 with [Fe/H] ~ -2.7 dex, found in the Keck Pilot Project (Cohen et al 2002, Carretta et al 2002) to have an excess of Mn, with $\epsilon(\mathrm{Mn})/\epsilon(\mathrm{Fe}) \sim$ twice the prevailing value among EMP stars. This has been confirmed by a better HIRES spectrum acquired in 2004; this dwarf also has a small excess of Ti relative to Fe. A few C-normal EMP stars (CS22169−035 and CS22952−015, for example, both of which are included in Fig. 1), have slightly low α-elements, but, as the figure clearly illustrates, in no case do they approach the anomalies seen in HE1424−0241.

4. Comparison With Predicted SNII Yields

At least several SN contribute to the chemical inventory of stars with [Fe/H] $\gtrsim -3$ dex, and the observed ratios of the chemical elements are determined by a sum over an assumed initial mass function of predicted SNII yields. SNIa and AGB stars also contribute at still higher metallicity and later times. But given the very low metallicity of HE1424−0241, ejected material from only a very small number of core collapse SN are presumed to have contributed to the material in this star. We must therefore find a model SNII whose predicted nucleosynthetic yields match the abundance ratios seen in this star. ^{28}Si is formed largely

[3] σ here is the sum in quadrature of the uncertainty in [X/Fe] for HE1424−0241 and that of the uncertainty of the linear regression for the "normal" EMP giants.

in regions interior to where the bulk of the ^{24}Mg is produced, although of course nothing of either of these species remains in the central region of the SN, which is mostly ^{56}Ni. Thus the details of the SN explosion model are important in determining the Si/Mg ratio in the ejected material. We require a range in the ratio of ^{28}Si/^{24}Mg in the ejected material of at least a factor of 10 to reproduce the behavior of both HE1424−0241, with its strong deficit of explosive α-burning elements but normal Mg (from hydrostatic α-burning) and of all previously known "normal" EMP stars.

The older models of Woosley & Weaver (1995) are much more effective at reproducing the observed distribution of abundance ratios in HE1424−0241. Mg/Si production varies by a factor exceeding 10 in these models, with Mg yields highest at masses near 35 $M_{\odot}$, while Si yields reach their maximum in SNII with lower progenitor masses near 20 $M_{\odot}$. These yields can qualitatively reproduce the behavior seen in HE1424−0241.

However, none of the SNII models in the grids recently calculated by Chieffi & Limongi (2004) and by Kobayashi *et al.* (2006) comes close to reproducing the abundance ratios among the α-elements seen in HE1424−0241. Both studies provide predictions of explosive yields for SNII progenitors with a wide range of initial masses from 13 to 35 or 50 $M_{\odot}$ with a wide range of metallicities. They included an extensive network of nuclear reactions. For the mass cut adopted in each of these two studies, they each predict yields after the radioactive decays for ^{28}Si/^{24}Mg whose range over the entire set of model explosions does not exceed a factor of two. However, the two studies differ in which mass range of SN progenitors produces larger ratios of ^{28}Si/^{24}Mg, Chieffi & Limongi (2004) favoring lower mass progenitors, while Kobayashi *et al.* (2006) suggests progenitor masses at the upper end of the range they consider. In no case does the predicted production ratio [Si/Fe] become less than −0.1 dex.

The most recent predictions of nucleosynthesis yields in SNII have undoubtedly been tuned to reproduce the behavior of the previously known stars EMP stars with [Fe/H] reaching down to ~ -4 dex. The abundance ratios we have derived for HE1424−0241, however, demonstrate that these models do not reproduce the full range of the behavior of nucleosynthesis achieved in real SNII and seen among the most peculiar of the the large sample of EMP stars we have studied in the 0Z project.

Production of the odd atomic number elements Mn and Co occurs through incomplete Si-burning for Mn and complete Si-burning for Co. Kobayashi *et al.* (2006) point out that the odd-to-even ratio among the Fe-peak elements depends on the mixing-fallback process, the explosion energy, and the neutron excess Y_e. While again no published model can reproduce the large excess of Co and Mn relative to Fe seen in HE1424−0241, we must hope that some combination of these parameters can be found that will accomplish this task.

5. Behavior of The α-Elements

Differential analyses of large samples of stars within a small range of $T_{\rm eff}$ in the thin disk of the Galaxy as compared to stars in the thick disk such as those of Edvardsson *et al.* (1993), Bensby, Feltzing & Lundstrom (2004), and Reddy *et al.* (2006) have been able to achieve very high precision. These surveys have demonstrated that the trends of [X/Fe] versus [Fe/H] are not identical between the various stellar populations of the Galaxy. But in such studies to date, all the α-elements are believed to have varied together and to show the same trends.

A few moderately metal-poor halo field stars have been found that appear to be α-poor; Fulbright (2002) suggests that lower [α/Fe] stars are found among those with high space velocities with respect to the local standard of rest, while Stephens & Boesgaard (2002) suggest such stars are associated with the outer halo. The most extreme α-poor stars, including that found by Carney *et al.* (1997), were reviewed by Ivans *et al.* (2003). However, these stars show depletions of Na, Al, Mg, Si and Ca with respect to Fe. They are sufficiently metal-rich compared to HE1424−0241 that their chemical inventory has a composite origin, with SNIa, SNII and AGB stars all contributing, and can be qualitatively explained by varying the SNIa/SNII ratio, an explanation which cannot be applied to HE1424−0241.

All this, while interesting, is not the key issue for the abundance distribution of the EMP giant HE1424−0241. Woosley & Weaver (1995) find that Si, Ca, and Ti are formed by explosive α burning in SNII, while O and Mg are produced by hydrostatic α burning. HE1424−0241 shows a clear large deficiency of the former elements, but no apparent deficiency of the hydrostatic α burning element Mg.

As abundance analyses have reached higher levels of accuracy (or at least of internal accuracy) and as sample sizes have increased, there have been reports of small differences, much smaller than those we find in HE1424−0241, between the behavior of the explosive and hydrostatic α-elements in certain specific environments. The recent analyses of Fulbright, McWilliam & Rich (2007) of a sample of 27 red giants with Keck/HIRES spectra in Baade's Window in the Galactic bulge found that the explosive α-elements Si, Ca and Ti have similar trends of [X/Fe] as a function of [Fe/H]. However they found that the hydrostatic α-elements O and Mg show a different behavior in the bulge giants. This separation within the Galactic bulge sample is small; $\sim$0.2 dex in total, much smaller than what we observe in HE1424−0241. Fulbright, McWilliam & Rich (2007) detected similar effects, again on a much smaller scale than in HE1424−0241, in a second environment, among stars in the Milky Way dwarf spheroidal satellite galaxies. They used the compilation of data from the literature by Venn *et al.* (2004), which relies heavily on the work of Shetrone, see, e.g. Shetrone *et al.* (2003).

These examples demonstrate that the production ratios of the explosive to hydrostatic α elements are not fixed; they must depend on environment, the IMF, the star formation history, or other relevant factors. The subtle differences seen in the Galactic bulge and in dSph giants between the behavior of these two groups of α elements, with the the explosive α-elements being more depleted than the hydrostatic ones, are seen in a much more dramatic fashion in HE1424−0241. HE1424−0241 is a very extreme example of this phenomenon in a situation where only a very few SN contributed to the chemical inventory of this star and where, because of the very low metallicity of HE1424−0241, most other possible explanations for this become irrelevant.

6. Summary

All C-normal EMP giants studied to date in the two major surveys, our 0Z project (Cohen *et al.* 2004) and the First Stars VLT project (Cayrel *et al.* 2004), show smooth trends of abundance ratios [X/Fe] with Fe-metallicity with modest dispersion around these trends and no strong outliers. HE1424−0241, with [Fe/H] ~ -4.0 dex, breaks this paradigm. It is a many σ outlier in several of the abundance ratios, with $\epsilon(\mathrm{Si})/\epsilon(\mathrm{Fe}) \sim 1/10$ and $\epsilon(\mathrm{Si})/\epsilon(\mathrm{Mg}) \sim 1/25$ that of all previously known extremely metal poor giants or dwarfs, but normal [Mg/Fe]. It also has a moderately large deficiency of Ca and a smaller deficit of Ti, combined with enhanced Mn and highly enhanced Co, both odd atomic number elements. With respect to Fe, C is normal or low in HE1424−0241 (the G band of CH was not detected) and the heavy neutron capture elements are low.

From the point of view of SNII nucleosynthesis, HE1424−0241 is deficient in the explosive α-elements, but has a normal [Mg/Fe] ratio, where Mg is produced in hydrostatic α-burning. Recent models of production yields in SNII fail completely to reproduce the behavior of the α-elements HE1424−0241, whose chemical inventory presumably resulted from a very small number of previous SNII combined with any contributions from a hypothesized Pop. III. They also fail to reproduce the huge excess of Co with respect to Fe. These predicted yields are sensitive to the mass cut, the adopted electron excess profile, and to other explosion characteristics assumed in the calculations for model SN. They presumably were tuned to reproduce the behavior of the previously known EMP stars, so their failure to come close to reproducing the highly anomalous abundance distribution in HE1424−0241 is perhaps understandable.

HE1424−0241 thus provides important clues as to the details of SNII explosions and their nuclear production yields. It is so metal poor that no explanation other than unusual core collapse SN nucleosynthesis yields can be invoked to explain its unique abundance ratios. Modifications to standard SNII models will need to be made to find explosion parameters which can reproduce the properties we have derived for the peculiar EMP giant HE1424−0241.

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Table 1. Abundances for HE1424−0241

Species	Log[ϵ(X)] (dex)	[X/H] (dex)	[X/Fe] (dex)	σ (dex)	Number of Lines	[X/Fe](0Z)[a] (dex)	[X/Fe](VLT)[b] (dex)
C	< 5.26	< -3.33	$< +0.62$	...	CH	...	$\sim$+0.20
N	< 5.10	< -2.83	$< +1.12$	...	NH	...	...
NaI[c]	2.32	−4.00	−0.05	0.07	2	−0.15	−0.20
MgI	4.03	−3.51	+0.44	0.12	3	+0.49	+0.24
AlI[d]	2.35	−4.13	−0.18	0.15	2	−0.13	−0.12
SiI	2.59	−4.96	−1.01	...	1	+0.45	+0.41
CaI	1.84	−4.52	−0.58	...	1	+0.32	+0.27
CaII	2.10	−4.26	−0.31	...	1	...	...
ScII	−0.95	−4.05	−0.10	...	1	+0.13	+0.04
TiII	0.85	−4.14	−0.17	0.17	8	+0.29	+0.24
VII	< 0.64	< -3.36	$< +0.59$	...	1	...	...
CrI	1.33	−4.34	−0.38	0.09	5	−0.45	−0.46
MnI[e]	1.59	−3.80	+0.15	0.02	2	−0.42	−0.47
MnII	1.69	−3.70	+0.25	0.13	2	...	...
FeI	3.49	−3.96	0.00	0.18	39	0.00	0.00
FeII	3.58	−3.87	+0.09	0.22	4	0.00	0.00
CoI	1.98	−2.94	+1.01	0.21	4	+0.50	+0.40
NiI	2.52	−3.73	+0.22	0.01	2	−0.08	−0.04
CuI	−0.41	−4.62	−0.67	...	1	...	...
SrII	< -2.75	< -5.65	< -1.70	...	2	...	...
YII	< -1.46	< -3.70	$< +0.25$	...	2	...	...
BaII[f]	−2.74	−4.87	−0.92	...	1	...	...
EuII	< -1.95	< -2.46	$< +1.49$	...	1	...	...

[a]Regression lines for C-normal giants from our 0Z survey, evaluated at −4.0 dex.

[b]Regression lines from Cayrel *et al.* (2004), Table 9, evaluated at −4.0 dex.

[c]Non-LTE correction of −0.2 dex has been applied for [Na/Fe] from the Na D lines.

[d]Non-LTE correction of +0.6 dex has been applied for [Al/Fe] from the 3950 Å doublet.

[e]The adjustment of +0.4 dex for the 4030 Å Mn I triplet suggested by Cayrel *et al.* (2004) and by our own work has been applied here.

[f]The Ba II line at 4554Å is only marginally detected and therefore the Ba abundance may also be interpreted as an upper limit.

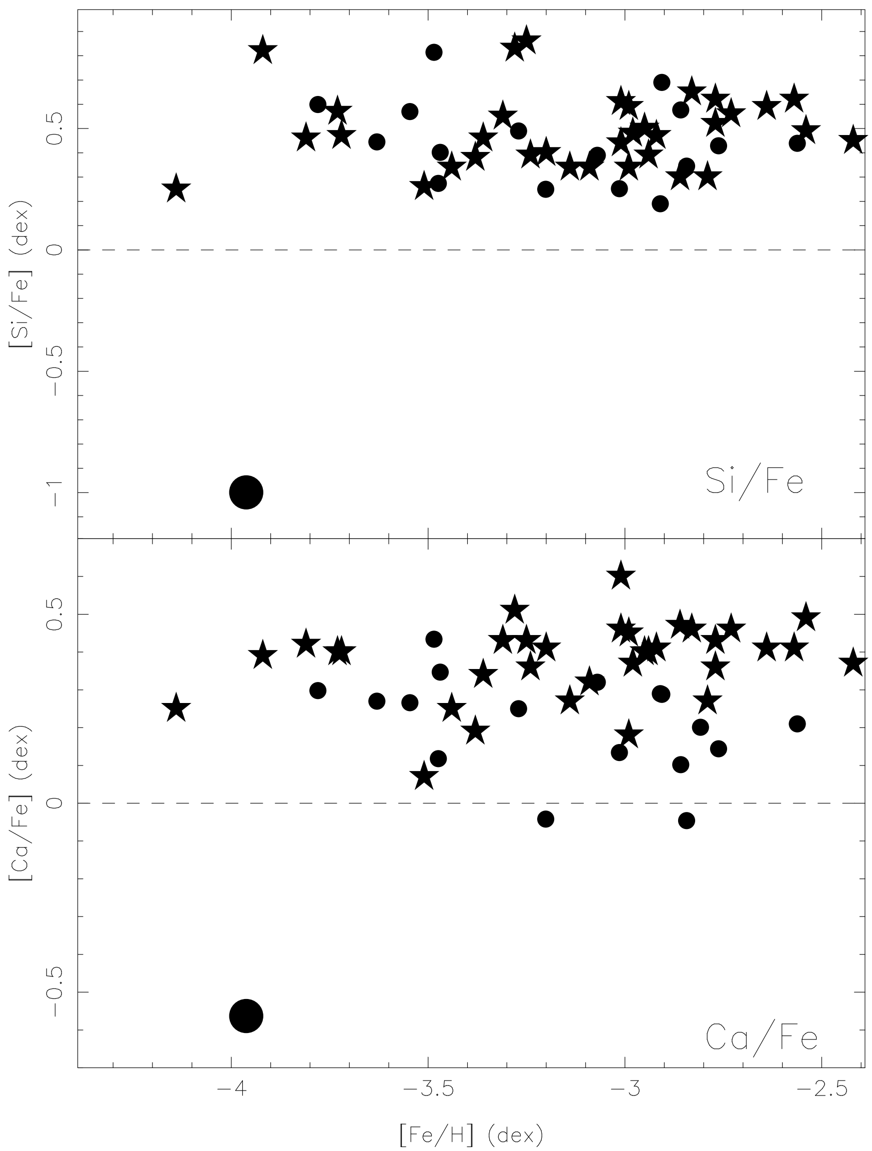

Fig. 1.— [Si/Fe] (upper panel) and [Ca/Fe] (lower panel) are shown as a function of [Fe/H] for EMP giants with [Fe/H] < -2.4 dex. Filled circles denote HES stars from our 0Z project and star symbols are giants from the First Stars VLT project (Cayrel *et al.* 2004). HE1424−0241 is shown as the large filled circle, and is the only outlier, being very low in both panels. The dashed horizontal lines represent the Solar abundance ratios.